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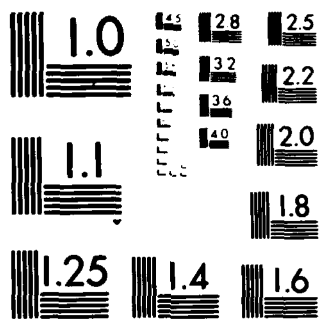

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WHITHER DYNAMIC FRACTURE MECHANICS?

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Submitted for presentation at the Second International Conference on Numerical Methods in Fracture Mechanics, Swansea, United Kingdom, July 6-11, 1980

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The experimental basis for the necessity of a dynamic characterization of crack run/arrest events is reviewed. Current anomalies in the use of linear elastodynamic treatments--apparent geometry and load rate dependence of the dynamic fracture toughness property--are discussed. A review of concurrent work in plastic fracture mechanics is given as a possible basis for circumventing these anomalies.

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WHITHER DYNAMIC FRACTURE MECHANICS?

M. F. Kanninen[(1)]

SUMMARY

The experimental basis for the necessity of a dynamic characterization of crack run/arrest events is reviewed. Current anomalies in the use of linear elastodynamic treatments--apparent geometry and load rate dependence of the dynamic fracture toughness property--are discussed. A review of concurrent work in plastic fracture mechanics is given as a possible basis for circumventing these anomalies.

INTRODUCTION

At the first conference on Numerical Methods in Fracture Mechanics, the author presented an extensive appraisal of the numerical solution techniques used to analyze dynamic fracture mechanics problems [1]. The techniques reviewed were exclusively based on elastodynamic behavior coupled with loading rate dependent (for crack growth initiation) and crack speed dependent (for unstable crack propagation) fracture toughness values. While some new work has appeared in the interim, it is the author's feeling that this does not make a marked departure from the previous trends in the field. Therefore, a reassessment of elastodynamic computational techniques per se is not warranted at this time. The reader interested in this background material can refer to the earlier paper.

An important concern at the time of the first conference was whether a quasi-static or a fully dynamic characteriza-

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tion of the arrest of a rapidly propagating crack is the more correct. Now, while most workers in the field believe that the dynamic view of crack arrest is more basic, a pragramatic accommodation has been reached with the quasi-static point of view. Hence, this is no longer a critical issue. New issues have emerged to take the place of this controversy, however. These are calling into question basic concepts in dynamic fracture mechanics that were largely taken for granted earlier. A discussion of these with suggestions for possible remedies will form the focal point of this paper. The title chosen for this paper reflects the fact that basic questions about the subject do indeed exist and that further work--possibly in new directions--is called for.

DYNAMIC FRACTURE MECHANICS

Crack Propagation Theories

Until very recently the controversy concerning the proper treatment of the arrest of a rapidly propagating crack dominated work in the field of dynamic fracture mechanics. This controversy centered on whether a dynamic treatment (i.e., one incorporating inertial forces in the equation of motion for the cracked body, stress wave interactions with boundaries, and a crack motion dependent fracture toughness property) or a static post-arrest characterization is basically correct. In a dynamic approach, crack arrest occurs as the terminaton of crack propagation. If this is correct, it follows that, in principle, there can be no direct connection between crack arrest and the quasi-static condition that exists at some long time after arrest. Conversely, if the static condition that corresponds to conditions at the time of arrest (e.g., crack length, applied stresses) uniquely characterizes the arrest process, no consideration of the crack propagation process per se is needed.

Figure 1 shows schematically results obtained by Hahn, et al [2] at Battelle's Columbus Laboratories which revealed clearly the importance of a dynamic-based analysis, at least for the DCB test specimen. As indicated in the figure, crack propagation from an initially blunted crack tip under slowly inserted wedge loading proceeds at an ostensibly constant velocity. This fact, albeit unexpected, made possible a decisive comparison of various possible analysis approaches. The simplest of these possibilities supposes that the crack propagates under quasi-static conditions with a fracture toughness that is always equal to the initiation toughness,

K_{IC}.[(ii)] As shown in the lower part of Figure 1, for quasi-static conditions with $K_{ID} = K_{IC}$, a higher crack speed is predicted. Also, the crack jump length is considerably underestimated. Hence, this approach is clearly invalid.

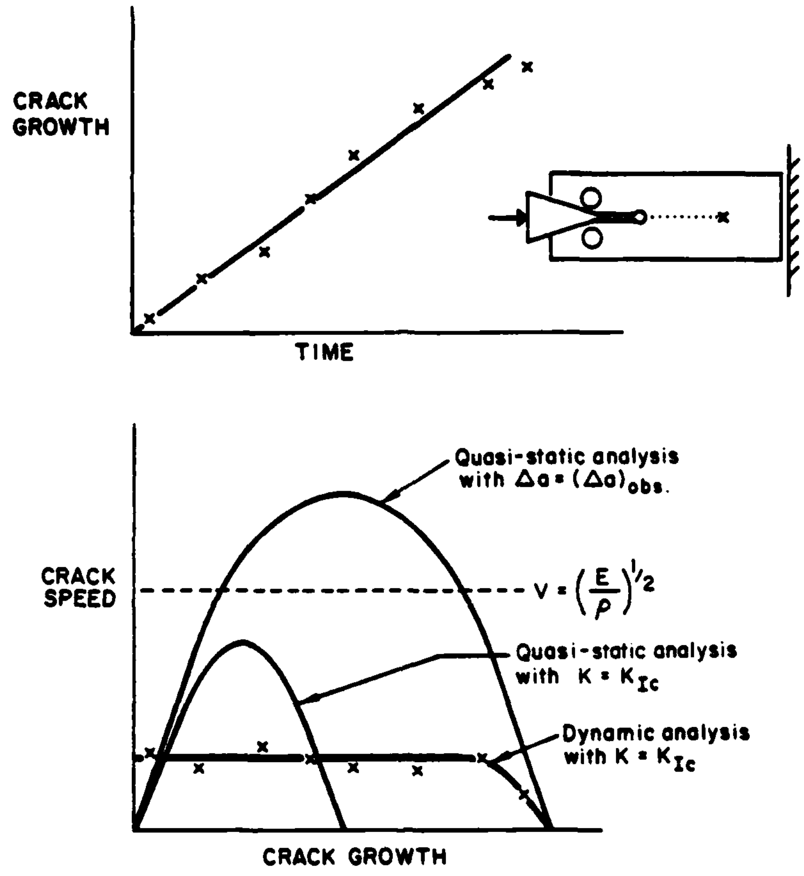

FIGURE 1. QUASI-STATIC VERSUS DYNAMIC ANALYSES OF RAPID CRACK PROPAGATION AND ARREST

(ii) Because of the blunted initial crack tip, the stress intensity factor at the onset of crack growth, K_Q, can be made arbitrarily greater than K_{IC} so that the crack speed and the crack jump length can be systematically varied. Note that with wedge loading the crack propagates into a diminishing stress field and, hence, the arrest of a fast moving crack within a DCB specimen is possible. Moreover, because these can be controlled by the bluntness of the initial crack the DCB specimen is ideally suited to an elucidation of crack arrest principles.

If instead a value of the fracture toughness of the running crack is selected in order to match the observed crack arrest point, much higher crack speeds are obtained. It usually happens that, as indicated in the figure, the predicted crack speeds can exceed the elastic wave speeds for the material. Clearly, therefore, the resolution of this difficulty does not lie in the choice of a fracture toughness property.

Results of the kind shown schematically in Figure 1 provided strong evidence that extended amounts of unstable crack propagation could not be characterized with a quasi-static computational approach. This fact led to the development of a simple dynamic analysis model to study crack propagation in the DCB specimen [3]. A typical result using this approach is also shown in Figure 1 where, to a quite good approximation, the experimental results were reproduced both qualitatively (i.e., a linear crack length-time record virtually from the onset of crack growth to just prior to arrest) and quantitatively.(iii)

The success of the dynamic analysis in predicting crack run/arrest events in DCB specimens exemplified in Figure 1, coupled with the unrealisticness of quasi-static analyses, led to questioning of the then widely accepted static post-arrest characterization of crack arrest. For example, Kanninen [5] performed a series of computations for different initiation conditions in the DCB specimen which showed that the static condition following arrest was a very definite function of the crack jump length in the test. This means that the post-arrest condition--conventionally characterized by the "arrest toughness" K_{Ia}--cannot be related to the material properties controlling the propagation event. Clearly, these two approaches are theoretically incompatible, and on the basis of the foregoing, it appears to be the dynamic approach that is the correct one.

Present Crack Arrest Assessments

Although the work of Hahn, et al [6] accumulated a substantial amount of evidence in support of the dynamic view of

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(iii) The equations of the one-dimensional model for dynamic crack propagation in the DCB test specimen that were used for the early work in this area were subsequently modified as a result of a more rigorous derivation. This work, together with numerical verifications using a two-dimensional analysis model, can be found in the paper of Gehlen, et al [4]. The correction, it might be noted, is just that anticipated in footnote (vi) of reference [1].

crack propagation and arrest, wide spread acceptance of this view awaited more direct experimental evidence. This was eventually forthcoming in the work of Kalthoff, et al [7]. Their results were obtained using the shadow pattern (or method of caustics) technique which, coupled with flash photography, enables a direct measurement of the stress intensity factor of a fast running crack to be made. If, as assumed in the dynamic point of view, crack propagation occurs only when

$$K_I = K_{ID}(V) \qquad (1)$$

then experimental results such as those of Kalthoff, et al can be used to determine directly the material property K_{ID} as a function of crack speed V. Figure 2 shows their results for DCB specimens using four different K_Q values.

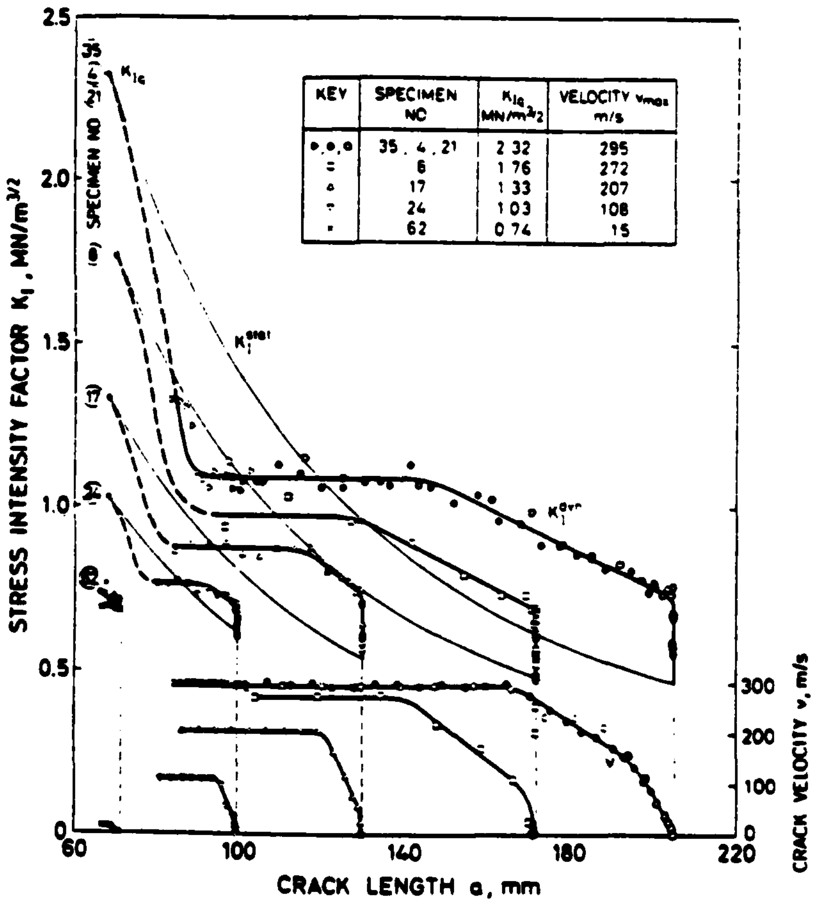

FIGURE 2. STRESS INTENSITY FACTORS FOR CRACK PROPAGATION IN A DCB TEST SPECIMEN FOR VARIOUS DIFFERENT K_Q VALUES - RESULTS OF KALTHOFF, et al [7]

The most important result shown by Figure 2 is that, while the dynamic value of the stress intensity factor at arrest is very nearly the same for all four experiments, the statically computed post-arrest value varies systematically with the crack jump length. This is completely consistent with the dynamic point of view and, of course, at odds with the static arrest characterization. However, it is now generally realized that the DCB specimen is perhaps the most dynamic of all possible structural configurations. Figure 3 illustrates this by comparing a finite difference solution taking into account the finite dimensions of the specimen with Freund's dynamic solution for an infinite medium.(iv)

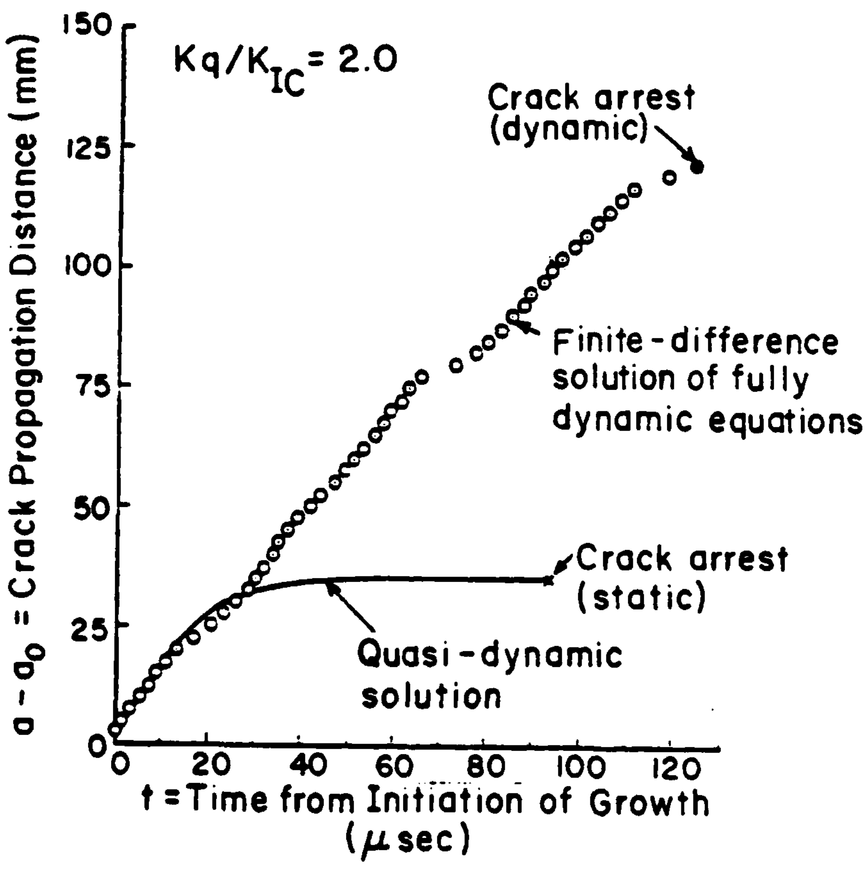

FIGURE 3. COMPARISON OF CALCULATED CRACK LENGTH VERSUS TIME IN A DCB TEST SPECIMEN WITH A DYNAMIC SOLUTION FOR AN INFINITE MEDIUM

(iv) The latter solution was obtained with Equation(11) in reference [1].

The result shown in Figure 3 reveals that the kinetic energy that is reflected back to the crack tip (and is therefore available for use in providing the material's resistance to crack growth) plays a crucial role in crack propagation in a DCB test specimen. That is, the time required for an elastic stress wave to travel from the crack tip to the specimen boundary and return is 26 μsec. It can be seen in Figure 3 that this is just where the infinite medium solution departs and, in fact, predicts arrest. Figure 4 which shows the partitioning of the initial strain energy contained in the specimen during the run-arrest event, further bears this out. It can be seen that the kinetic energy rises to a maximum at about the statically predicted arrest point (i.e., $a - a_o$ = 35 mm). The subsequent decrease indicates the kinetic energy

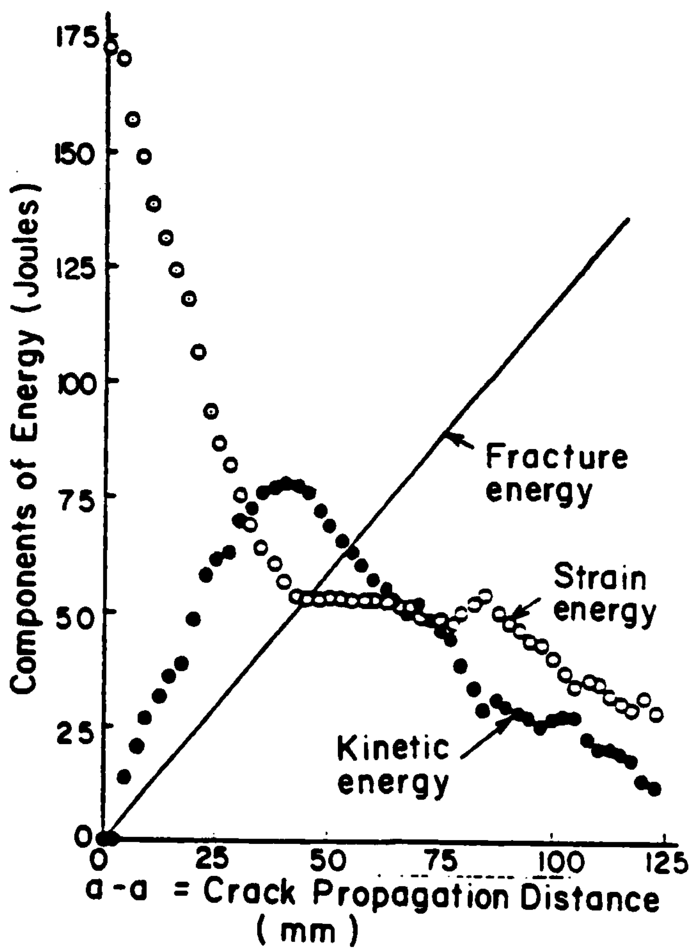

FIGURE 4. DISTRIBUTION OF ENERGY DURING CRACK PROPAGATION IN A DCB TEST SPECIMEN

reflected from the specimen boundaries is being utilized to continue the crack propagation event. Figure 5 shows a result obtained by Kobayashi, et al [8] which indicates that similar behavior occurs in a compact tension specimen.

The accommodation with regard to a static post-arrest characterization mentioned above has been on a pragmatic basis. As examples, Crosley and Ripling [9] and Witt [10] recognize that, because dynamic effects exist in crack arrest, the

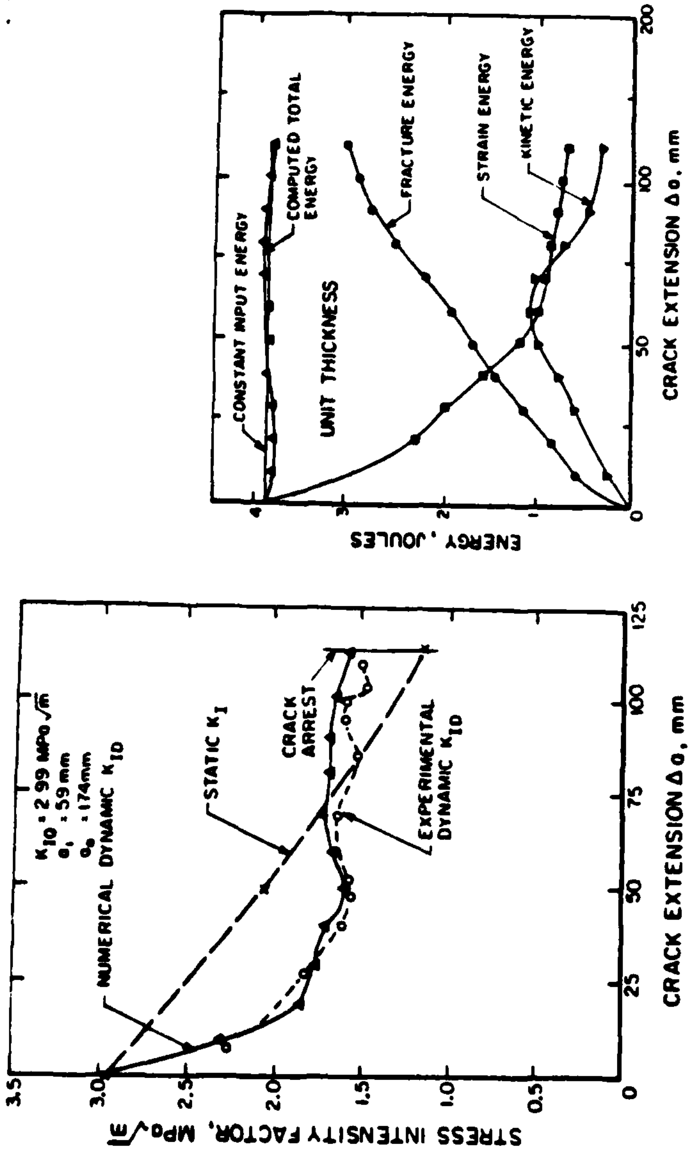

FIGURE 5. COMPARISON OF CALCULATED AND MEASURED RESULTS FOR DYNAMIC CRACK PROPAGATION IN POLYCARBONATE MODIFIED COMPACT TENSION SPECIMENS
Results of Kobayashi, et al [8]

quasi-static approach is an over-simplification. Nevertheless, as they assert, reasonably constant statically determined arrest values can be determined experimentally that will suffice for practical purposes if the crack jump length that is allowed is kept small. Moreover, in actual structures, the return of kinetic energy to the crack tip is likely to be small so that the static approach will not be unreasonable.

This same point of view was adopted by Marston, et al [11] in applying a quasi-static approach to assess crack propagation and arrest in a nuclear pressure vessel subjected to thermal stresses in a hypothetical loss-of-coolant accident (LOCA). They concluded that, while dynamic analyses may in general be necessary for crack arrest problems, because of the geometry of the vessel and the anticipated short jump length, a quasi-static analysis should suffice. This assumption is corroborated by the dynamic analysis of the short-jump LOCA event reported by Cheverton, et al. [12] But, as Cheverton, et al also point out, for a hypothetical long crack jump, a dynamic analysis predicts a much deeper penetration than would a quasi-static analysis.

To summarize, while the dynamic approach to crack arrest is clearly the basically correct one, it is also clear that the not inconsiderable computational and experimental complexity required for a fundamentally correct analysis is not always necessary for practical applications. Indeed, for small crack jump lengths, a dynamic fracture mechanics treatment will be indistinguishable from a simpler quasi-static analysis. But, when the two approaches differ, it must be that the dynamic approach is more nearly correct. And, because it generally predicts that the crack will propagate faster and further than will a static analysis, it may be dangerous to assume a priori that quasi-static conditions prevail in any given circumstance.

Adequacy of Elastodynamic Fracture Mechanics

As described in the foregoing, dynamic fracture mechanics has advanced and, in doing so, new critical issues have emerged to replace the crack arrest controversy. Of more prominence is the growing realization that the applicability of even the most rigorous analysis procedures that have been developed may be much more limited than was previously realized. That is, virtually all mathematical solutions and interpretations of experimental results are now made in terms of linear elastic fracture mechanics (LEFM) treatments. However, most work is done on either ductile tough materials like the nuclear pressure vessel steel A533B or on viscoelastic polymeric materials like Homolite 100. While these materials do not satisfy the basic assumptions of LEFM, for lack of an alternative, elastodynamic analyses have been used. Hahn, et al [13] present a crack arrest data base from crack

propagation and arrest measurements on various pressure vessel steels. Similar data are given by Francois [14].

A tacit assumption in the collection of a crack arrest data base is that the elastodynamically inferred property $K_{ID} = K_{ID}(V)$ is a material property. As such, it clearly must be independent of the crack/structure geometry and of the manner in which the load is applied. At least two pieces of evidence exist, however, which casts some doubt on this assumption. The first is exemplified by the results of Kalthoff [15] shown in Figure 6. In these experiments cracks were propagated in both rectangular DCB specimens (RDCB) and single edge notch specimens (SEN). It can be seen that the values determined by the method of caustics (see above) were found to be distinctly different in the specimens.

To determine if batch-to-batch material property variations were influencing their results, Kalthoff also used a tee-shaped specimen (RDCB/SEN). In this specimen cracks propagate for a time in each a DCB-like geometry and, later, in a SEN-like geometry (see Figure 6). He found that the results from each portion of the event correlated quite well with the simple specimen results of the corresponding geometry. Hence, material property variations are not important and, he concludes, there is a definite geometry effect.

Other investigators have also reported results which indicate that the K_I property exhibits some geometry dependence; see, for example, Kobayashi, et al [8]. Dahlberg, et al [16] have argued that geometry-dependence and even a dependence on higher order time derivatives must be accepted to avoid the necessity for nonlinear dynamic analyses. They point out that, even if K-dominance (see below) of the inelastic region around the crack tip exists, a dependence of the dynamic fracture toughness on the second and higher order derivatives of the crack length cannot be excluded by any theoretical argument.

While the geometry dependence exhibited in Figure 6 is certainly significant from a conceptual point of view, the practical limitation imposed by these results is probably not debilitating. It can be argued that, in view of the many other uncertainties that are present in any structural analysis problem, this relatively small difference is not significant. One would simply take a lower bound of such results and thereby impose only a modest penalty on the structure.

Of possibility greater significance, therefore, are the results obtained by Kanninen, et al [17] in a study of dynamic crack propagation initiated by impact loading. Specifically, they used AISI 4340 steel three point bend specimens which were instrumented to measure crack length versus time. First,

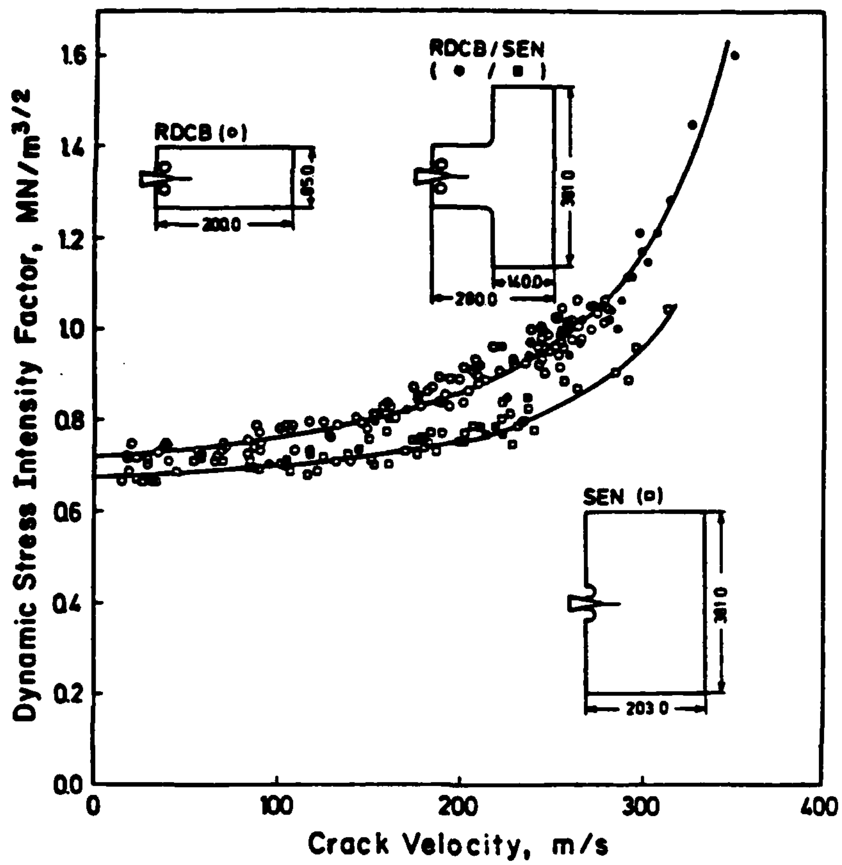

FIGURE 6. DYNAMIC FRACTURE TOUGHNESS VALUES IN ARALDITE B AS DETERMINED BY THE METHOD OF CAUSTICS
Results of Kalthoff [15]

to assess any possible material property variations and to determine the effect of geometry-dependence of the fracture toughness property determined in an earlier program using the DCB test specimen, dynamic crack propagation was initiated under quasi-static loading. A comparison between the experimental results and those predicted with an elastodynamic finite difference calculation using this property is shown in Figure 7. It can be seen that the agreement is excellent.

Because of the agreement shown in Figure 7 and the belief that the material used very well satisfies the basic requirements of a linear elastic fracture theory, it might be logical to expect that the same K_{ID} value would also apply in impact loading. However, as shown in Figure 8, the calculation seriously underestimates the material's resistance to fast

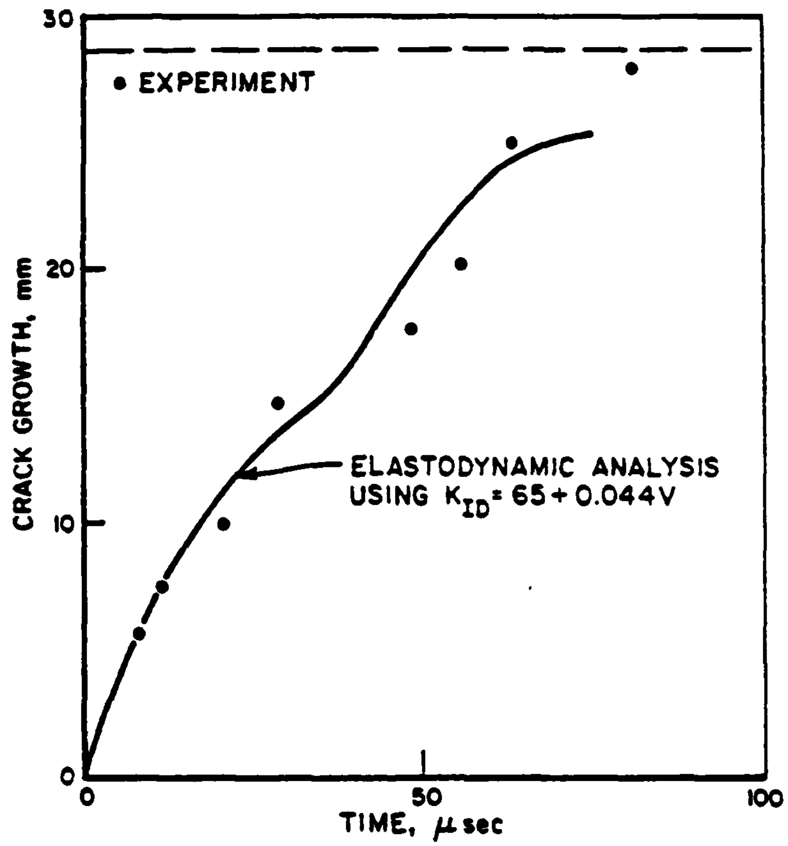

FIGURE 7. COMPARISON OF MEASURED AND CALCULATED CRACK GROWTH VERSUS TIME IN A QUASI-STATICALLY LOADED THREE-POINT BEND SPECIMEN

fracture.[(v)] A prediction much more in agreement with the experimental results was obtained by back calculating a toughness value from the experimentally determined throw energy (i.e., by deducting the kinetic and strain energy in the

(v) In contrast to the quasi-static loading results shown in Figure 7, where zero time corresponds to the initiation of crack growth, zero time in Figure 8 is the time that the striker contacts the specimen. Clearly, in an impact event, a time lapse is required for the crack tip stress intensity to build up to a critical value.

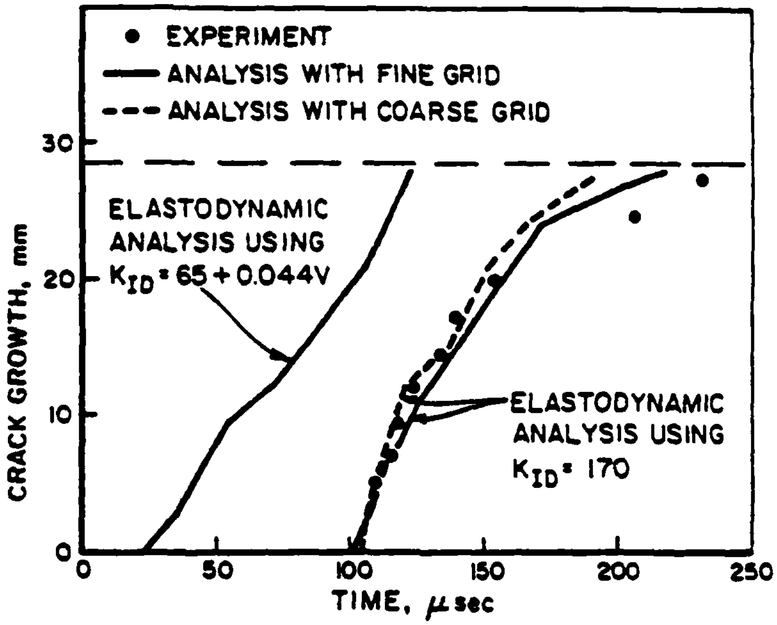

FIGURE 8. COMPARISON OF MEASURED AND CALCULATED CRACK GROWTH VERSUS TIME IN AN IMPACT LOADED THREE-BEND SPECIMEN

broken specimen from the energy supplied by the striker). This gave a value of $K_{ID} = 170\ MNm^{-3/2}$, a value roughly double that of the quasi-statistically initiated event. Figure 8 shows that excellent agreement is obtained using this value.

There were several artifacts involved in the impact testing that could possibly cause this anomolous result. As described in reference [17], however, none were found to be significant. In addition, as shown in Figure 8, two different finite difference mesh sizes were used without appreciably altering the result. It was therefore concluded that the difference exhibited between quasi-statically initiated and dynamically-initiated rapid crack propagation does seem to proceed with a markedly different toughness property.(vi)

(vi) It can be seen from the results shown in Figure 7 and 8 that the crack speeds in the two events were similar. Regardless, AISI 4340 steel is not greatly rate-dependent. Thus, there is no simple explanation for the quite different toughness values that seem to be required as a speed-dependence.

The disparity exhibited by the impact testing results, when coupled with the geometry-dependence assessments made by Kalthoff and others, appears to cast serious doubt on the general applicability of linear elasticity-based crack propagation/arrest procedures. At the same time it should be recognized that, in any use of experimental observations to assess the basis of mathematical analysis procedures, no direct measurement of the stress intensity factor is possible. While observations of fringe and shadow patterns associated with a propagating crack can be made, the relation of these measurements to fracture mechanics parameters always requires the use of some mathematical model. And, any such model must be based upon a constitutive relation and other presumptions about the interaction between the propagating crack and the component that contains it.

To assess the possible effects of polymeric materials, Popelar and Kanninen [18] have devised a dynamic visoelastic representation for polymer DCB test specimens. Their results indicated that differences do exist but they can be accounted for by using the correct choice of the modulus--the static or long-term viscoelastic modulus, at least for cracks initiated under quasi-static conditions. However, they were unable to substantiate the finding of Fourney [19] that a substantial portion of the initial strain energy is lost by viscous damping prior to crack arrest in the photoelastic polymer Homolite 100. It is entirely possible that a more appropriate viscoelastic model is needed (Popelar and Kanninen used a three-parameter solid representation) before this can be done.

PLASTIC FRACTURE MECHANICS

Crack Tip Fracture Criteria

While the initial work in fracture mechanics was based upon an energy balance criterion, later work identified more esoteric fracture parameters--principally, the stress intensity factor, the crack opening displacement, and the J-integral parameter. In LEFM, these are all interrelated. Specifically, for plane strain conditions in the "opening" mode

$$G = J = \frac{1-\nu^2}{E} K^2 = Y \cdot \delta \qquad (2)$$

where G is the strain energy release rate, J is the value of the J-integral, K is the stress intensity factor, and δ is the crack tip crack opening displacement while E, ν, and Y are, as usual, the elastic modulus, Poisson's ratio, and yield stress, respectively.

Which of the four basic parameters involved in LEFM is the "most basic" may be thought to be a purely academic question. However, it assumes considerably more importance when it becomes necessary to select a crack tip fracture parameter as

the basis of a plastic fracture methodology capable of treating stable crack growth accompanied by extensive crack tip plasticity. Many different choices have been made, all having their origins in one of the LEFM parameters. But, because a set of equalities like (2) for conditions more general than LEFM does not exist, it is important to determine which criterion is on the firmest footing. This, in turn, suggests a more careful study of LEFM.

The modern view of LEFM is contained in Figure 9. It can be shown that, if the body everywhere obeys a linear elastic stress-strain law (see insert in Figure 9), then the stresses at the crack tip can be expressed in terms of a polar coordinate (r,Θ) system with origin at the crack tip as

$$\sigma_{ij} = \frac{K}{\sqrt{2\pi r}} F_{ij}(\Theta) + \ldots. \tag{3}$$

where the omitted terms are of higher order in r. For small values of r (i.e., very near the crack tip), only the first term is significant. Then, the remote stresses, the crack length, and the external dimensions of the cracked body will affect the stresses at the crack tip only through the parameter K, the stress intensity factor. More definitely, there will be a region--the "K-dominant" region--having the characteristic dimension D in which the first term of the series is a sufficiently good approximation.

To continue this argument, let R denote the size of the inelastic region surrounding the crack tip where the assumption of linear elastic behavior is invalid. It is in this region that the fracture event takes place. While it is not possible to directly characterize the fracture process using a linear elastic formulation, this is not necessary provided the inelastic region is contained in the K-dominant region. That is, if $R<D$, then any event occurring within the inelastic region is controlled by the deformation in the surrounding K-dominant region. Consequently, if crack growth occurs, it must do so at a critical value of the stress intensity factor.

The importance of this result is not for its own sake but rather for the generalization that is suggested for elastic-plastic conditions. In particular, using a power law hardening solution, an analogous argument to that given above can be followed. As illustrated in Figure 10, the crack tip stresses in this situation can be expressed as

$$\sigma_{ij} = J^{\frac{1}{n+1}} r^{\frac{1}{n+1}} F_{ij}(\Theta,n) + \ldots. \tag{4}$$

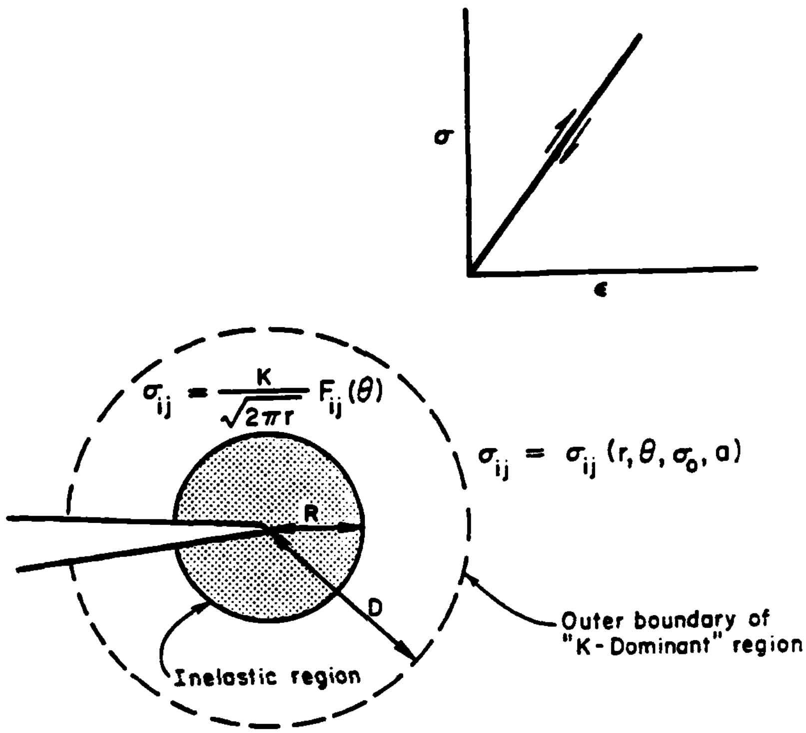

FIGURE 9. BASIS OF LINEAR ELASTIC FRACTURE MECHANICS

where n is a property of the material's stress-strain curve. Now, the effect of the remote stresses, the crack length, and the external dimensions of the body on the stresses within a "J-dominant" region depend only on the parameter J. If this region surrounds the inelastic region, then the conditions governing the fracture event must correspond to a critical value of J. The crack growth criterion can therefore be expressed as

$$J(a, \sigma_o) = J_c \tag{5}$$

where a denotes the crack length and σ_o the applied stresses.

Notice that, in contrast to the LEFM argument, the inelastic region is not the plastic region here. It is instead the much smaller region in which the deformation plasticity approach (see insert in Figure 10) is invalid. That is, the region in which the hole growth and coalescence processes involved in ductile crack extension are occurring--processes that clearly cannot be taken into account directly in a continuum mechanics approach. However, where J-dominance exists,

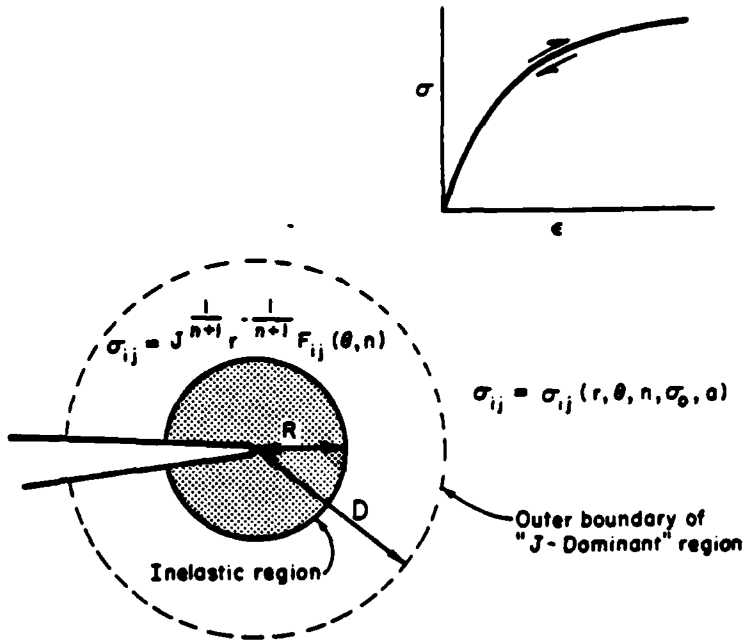

FIGURE 10. BASIS FOR THE USE OF THE J-INTEGRAL IN PLASTIC FRACTURE MECHANICS

the initiation and growth of a crack can be expected to be governed by a material property--the J-resistance curve--which gives critical J values as a function of crack growth.

For a growing crack, elastic unloading takes place in the "wake" plastic region left behind the crack tip. This is also an inelastic process that cannot be addressed within the deformation plasticity-based approach just described. Consequently, it is to be expected that the size of the inelastic region becomes larger and inexorably overtakes the limits of the J-dominant region. At this point the J parameter also becomes invalid. Precise delineations of the amount of crack growth possible before the loss of J-dominance occurs do not now exist. This will depend upon the dimensions of the body and the rate of change of the J-resistance curve. For example, as suggested by Hutchinson and Paris [20], J-dominance will exist provided

$$\omega \equiv \frac{b-a}{J} \frac{dJ}{da} >> 1 \tag{6}$$

where a denotes the crack length and b is the dimension of the body nearest the crack tip.

Status of Plastic Fracture Mechanics

The key to developing an analysis procedure for plastic fracture is to identify an appropriate crack tip fracture criterion. Work performed by Kanninen, et al [21] has encompassed three main stages. First, center cracked panels were tested to obtain data on crack growth initiation and stable growth. Second, "generation-phase" analyses were performed in which the experimentally observed applied stress/stable crack growth behavior was reproduced in a finite element model with each of a number of candidate crack initiation and stable growth criteria being evaluated for the material tested. In the third stage, "application-phase" finite element analyses were performed using one of the candidate criteria to determine applied stress/crack growth behavior for a given specimen geometry.

The fracture criteria examined included the J integral, the local and average crack opening angles, the conventional LEFM R curve, and various generalized energy release rates. Each of the candidate criteria is attractive in one way or another. Hence, the task of selecting the best criterion for application to nuclear steels is not an easy one. Clearly, geometry independence is a crucial test of the acceptability of a plastic fracture criterion. Physical relevance is another. Practicality is a third. With these as primary qualifications, some assessments can be drawn from progress made so far.

The advantages of the J integral are its virtual independence of finite element type and element size, the computational ease involved in evaluating it, and, because of its history-independence, its catalogability. However, while the J integral is widely acceptable as a criterion for crack growth initiation, as already noted, it is valid only for a limited amount of stable crack growth. A J integral-based approach is unable to cope with large amounts of stable crack growth attended by large-scale plasticity because it is based upon deformation plasticity. Deformation plasticity (nonlinear elasticity) requires small plastic strains and precludes material unloading. This manifests itself in pronounced specimen dependence after a small amount (e.g., 10% of the remaining ligament size) of stable growth.

The crack opening angle is appealing because of its rapidly grasped physical significance and the opportunity that it offers for direct measurement. However, it should be recognized that there are two different definitions of the crack opening angle: a crack tip value that reflects the actual slope of the crack faces (CTOA), and an average value based on the original crack position (COA). While the critical value of the COA can be measured, it is difficult to see how its value has any direct connection with the fracture process.

Conversely, while the critical value of the CTOA can likely be associated with the fracture process, it presents a formidable measurement task. In addition, there are clearly some difficulties in making either value apply to mixed character shear/flat crack growth.

A proper stable crack growth criterion must differentiate between the energy dissipated in direct fracture-related processes near the crack tip and energy dissipated in geometry-dependent plastic deformation remote from the crack tip. With this in mind, a number of investigators have opted for a generalization of the LEFM energy release rate as the basic plastic fracture methodology. But, there is a basic difficulty inherent in this approach. There is a theoretical basis for expecting a computational step size dependence in an energy release rate parameter that is based on the work of separating the crack faces. It can be argued that this can be handled by appealing to micromechanical considerations. Regardless, it appears that the necessity to arbitrarily circumvent the inherent step size difficulty with any energy release rate parameter makes its use somewhat unattractive.

Dynamic Plastic Crack Propagation

Work in dynamic elastic-plastic crack propagation has been performed by Achenbach, et al [22,23]. The material model used in the work was based on Prandtl-Reuss incremental plasticity and a bi-linear stress-strain relation with irreversible material unloading behind the crack tip. Results have been obtained for crack propagation in plane stress, plane strain and in anti-plane strain conditions. These results show that the order of the crack tip singularity and the position of the plastic unloading interface, while highly dependent on the slope of the stress-strain curve in the plastic regime, are only moderately dependent on the crack speed. Results for plane stress conditions are shown in Figure 11, where $\alpha = E_t/E$.

These findings are important primarily in that they demonstrate that a fundamentally correct elastic-plastic dynamic formulation of a propagating crack can be achieved for use in a finite element program. In addition, because for specified material stress-strain behavior, the crack tip characterizing parameters will be essentially unaffected by modest changes in the crack speed, this work shows that it will be possible to devise an efficient computational model.

Further work will be needed to identify a plastic fracture criterion for dynamic crack propagation. This parameter must be one whose critical values are geometry-independent material property values over a wide range of geometries and crack growth lengths. A strong possibility that has been identified during the course of experiments and

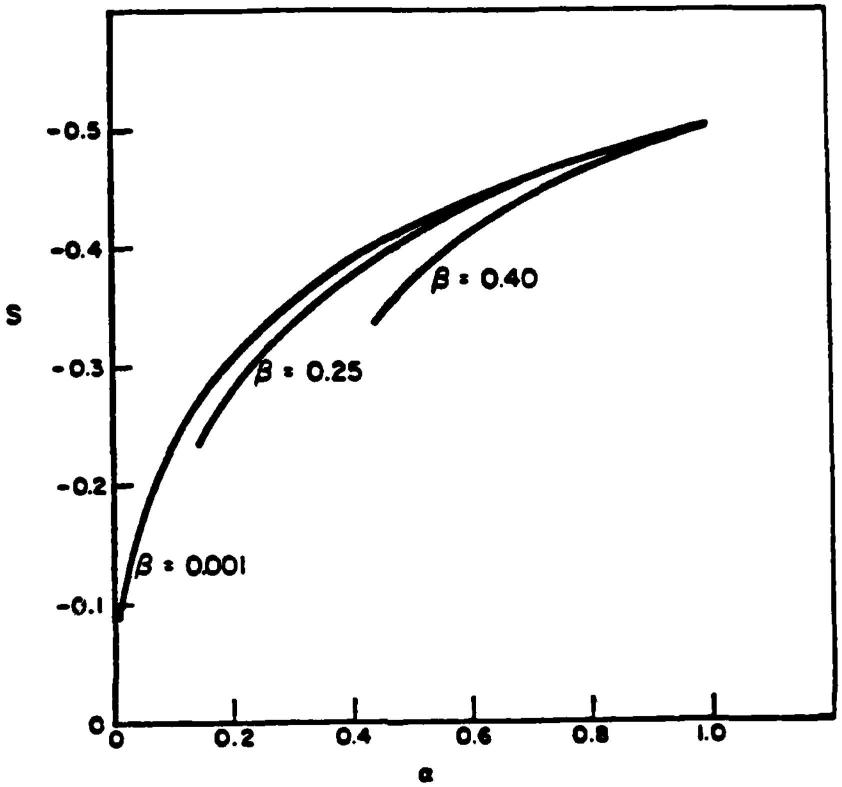

FIGURE 11. ORDER OF THE CRACK TIP SINGULARITY IN PLANE STRESS DYNAMIC CRACK PROPAGATION

generation-phase analyses on compact tension specimens and center-cracked tension panels is the crack tip crack opening angle (CTOA). Kobayashi, et al [8] have shown how effectively this parameter can be used in their analysis of circumferential crack propagation in a pipe.

DISCUSSION

Most potential fracture problems involve cracks emanating from flaws in or near a weld where it is difficult to apply a fracture mechanics assessment for several reasons. First, residual stresses probably exist of unknown magnitude. Second, the toughness of the material in the heat affected zone is uncertain. Third, welding processes generally cause plastic deformation which invalidates the currently available linear elastic fracture mechanics capabilities. These difficulties suggest the use of a crack arrest strategy whereby, even if unstable crack propagation occurs, it will be arrested in the base material. This is the rationale for the dynamic fracture mechanics analysis discussed here.

The schism between the dynamic and the quasi-static characterizations of crack arrest is no longer a critical issue. It is generally agreed that there are conditions where a quasi-static interpretation of a laboratory test result can give an appropriate measure of the arrest toughness property and, under certain types of loading and crack-structure geometries, dynamic effects in crack arrest will indeed be negligible. Specifically, when inertia forces, stress wave reflections, and rate-dependent fracture processes are negligible, then the two approaches will give exactly the same prediction. There appears to be a fairly wide range of conditions in which, because the predictions are not greatly different, for practical purposes, the extra effort required to obtain a dynamic solution is unwarranted. However, where the two predictions are significantly different, it is the dynamic solution which is the more accurate.

It is important to recognize that a quasi-static calculation will generally underestimate the true crack driving force. Consequently, in extracting an arrest toughness value from an experiment, a value that is lower than the actual material property will be obtained. This will be conservative. Applying a quasi-static analysis using a given toughness value to assess the possiblity of crack arrest, on the other hand, will over-estimate the likelihood of crack arrest. While these two errors do tend to offset each other, it would always be prudent in addressing new situations to check the possibility that dynamic effects could be important.

The basic assumption in elastodynamic analyses of crack propagation has been that the dynamic fracture toughness is a unique geometry-independent material property that can, at most, depend upon crack speed, temperature, and plate thickness. However, results presented by several investigators are beginning to seriously question the legitimacy of this assumption. Some investigations indicate that the external dimensions of the component can affect values inferred for the toughness property. Others suggest that unstable crack propagation emanating from impact loading occurs with a toughness which differs markedly from that corresponding to conventional quasi-static loading. Whether or not residual plasticity or other nonlinear effects could play a key role in mollifying this seeming lack of uniqueness cannot presently be determined.

CONCLUSIONS

1. Crack propagation accompanied by significant plastic deformation cannot be rigorously treated at present--only elastodynamic solutions can now be applied. However, these appear to give reasonable predictions even for tough ductile materials (e.g., nuclear vessels, gas pipelines), under certain conditions.

2. Quasi-static predictions of crack arrest can be valid in some circumstances--e.g., when crack jump length is small in comparison to component dimensions--but will give an underestimate when dynamic effects are significant.

3. Controversy now exists on the validity of $K_{ID} = K_{ID}$ (V) as a unique material property. Some geometry dependence has been cited. Also, comparisons of slow versus impact loading have revealed unexplainable differences.

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